Title

Future Roles of Milli-, Micro-, and Nano- Grids

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SUMMARY

Although it has slowed considerably, consumption of electricity continues to grow in developed economies. Further, there are some unknowns which might accelerate this growth, such as electrification of vehicle fleets and geothermal heat pump space and water heating. Most analysts anticipate that distributed energy resources (DER) will provide a large share of the expanded generation capacity required to meet this seemingly inexorably increasing electricity demand. Further, given the urgency of tackling the climate change problem, most of the added assets must be carbon-free renewables or nuclear, end-use efficiency improvements, or highly efficient fossil-fired technologies. In developed economies worldwide, the current power delivery paradigm has been in place for more than a century, i.e. since the emergence of polyphase AC systems around the turn of the last century. A key feature of this structure is that, in principle, universal service is delivered at a consistent level of power quality and reliability (PQR) throughout large regions. This paper describes a future possible structure for the electricity generation and delivery system that leaves the existing high voltage meshed grid paradigm in place, but involves radical reorganization of parts of the distribution network and customer sites. Managing a much more diverse dispersed system poses major challenges to the current centralized grid paradigm, particularly since many of these assets are small to tiny by macrogrid standards and they may ultimately number in the millions. They are also not ones that centralized control can rely upon to function in traditionally dependable ways, e.g. renewable generation can be highly variable and changes in output of generators are not independent. Although most involved in the industry agree that a paradigm shift is both necessary and desirable to manage the new system, the nature of the future system remains quite unclear. In the possible structure described here, the traditional grid, or macrogrid, remains similar at the high voltage meshed level. Three new entities are added more locally: community grids or *milligrids* that operate a segment of the existing distribution system, *microgrids* which are akin to current customer sites but which have automonous control, and *nanogrids*, such as telecom or Ethernet networks that currently distribute power to many low-power devices. The latter exist currently in the local electrical systems but are not typically considered a part of the traditional electricity supply system. Because all these new entities exhibit some localized control, providing appropriate local heterogeneous PQR becomes a possibility. These new grid concepts enable a more "bottom-up" approach to electricity distribution, in contrast to the historic "top-down" model. The future will almost certainly include a mix of the two, but the balance among them and the interface (if any) between them is unclear.

KEYWORDS

microgrid, milligrid, nanogrid, macrogrid, megagrid, distributed generation, power quality, reliability

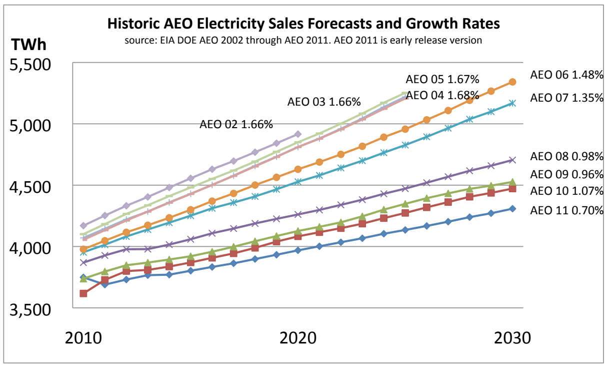
INTRODUCTION

Our legacy power system paradigm dates from George Westinghouse's successful Niagara Falls Power Project, implementing Tesla's concept for long-distance AC power delivery at 25 Hz and high voltages enabling energy transmission 32 km to Buffalo. From this ambitious beginning the power supply infrastructure has been built out at a massive scale, further entrenching the highly centralized paradigm for power systems. In the case of California, the whole Western Interconnect, which serves over 70 million people, is synchronized, and the California Independent System Operator (CAISO) controls almost 80 % of the state's electricity distribution network, or over 200 TWh/a. This paradigm is now being questioned for multiple reasons becoming apparent in the quite rapid current transformation of the power system. Our power system may evolve from its existing centralized structure to one in which numerous local control centers co-exist at lower voltage extremities of the network, while the backbone high voltage meshed grid continues to function as today.

LIMITS OF THE CENTRALIZED PARADIGM

The centralized paradigm is currently coming under review because of multiple changes that are taking place in the industry. It is important to remember that electricity demand continues to grow in developed economies, although current U.S. expectations are for somewhat slowing demand growth. Figure 1 shows how recent forecasts by the U.S. Energy Information Agency have predicted slower demand growth in recent years. Such forecasts are, however, uncertain because of the possible electrification of transportation, as well by other possible innovations, such as ground source heat pump space heating, not to mention our seemingly insatiable appetite for electronic gadgets.

Figure 1: Recent Annual Energy Outlook Forecasts of U.S. Electricity Consumption



To some extent, current policy objectives are contradictory. Expanding supply to meet expected growing demand is unavoidable, while it is also a priority to increase renewable generation penetration, and to develop and maintain competitive wholesale electricity markets. While all of the above objectives together with increasing difficulty siting new generation and transmission tend to work against a highly reliable high power quality power system, at the same time, we seek to provide the same PQR we enjoy today, or better. In fact, many have argued that the traditional power system must deliver higher PQR, as may be required by a *digital society*.[1] These contradictions have led some to question the traditional paradigm. Following is a short list of some of the key concerns that will challenge the traditional paradigm in the coming era.

Concerns about climate change and other environmental issues will result in increased penetrations of renewable generation in the fuel mix; for example, California has set targets for renewable generation (by its own State definition) of 20 % by 2010, and 33 % by 2030.[2,3] The three major electricity suppliers reached approximately 18 % in 2010, but the 20 % goal is within sight, and the 33 % in 2030 target is still effective. Unfortunately, many of these new resources do not fit well into the traditional paradigm. Renewable generation is both variable and relatively unpredictable, compared to traditional fossil resources, which implies that control operators must have more reserves available, which can be costly.[4] Another problem with renewable generation is that much of it is expected to come from relatively small installations, e.g. residential rooftop photovoltaic (PV) systems. Controlling numerous, possibly millions, of small sources poses a significant new challenge, and has led analysts to consider alternatives that could manage these smaller scale and problematic sources locally. The residual system would continue to be managed centrally so it would operate with similar numbers and sizes of resources as are successfully controlled today.

Unsustainability of heat losses by energy conversion from fossil fuels to electricity is also a growing concern. While some modern technologies can achieve excellent efficiencies as measured by historic standards, the overall systemic efficiency of generation at remote sites, long distance transmission, and local radial distribution delivers barely a third of the initial fossil energy to ultimate devices. One partial solution to this problem is smaller-scale generation closer to loads, which increases the potential for combined heat and power (CHP), which can improve overall efficiency significantly. In many climates, using the waste heat to cool buildings can be attractive because doing so further reduces expensive on-peak electricity use and downsizes needed generating capacity.

Infrastructure interdependency has become a growing concern, especially because our current power delivery system is highly vulnerable to both natural and malicious threats. The consequences of blackouts are serious in large measure because so many other critical infrastructures, such as communications, transportation, water treatment, etc., depend upon it. To the extent that vital services could be powered independently of the grid, the consequences of blackouts could be reduced.[5] *Reliability is costly* even though customers do not usually see it as a line in their electricity bills. Maintaining high levels of reliability incurs two types of costs, both significant. First, equipment investments to improve PQR, such as underground versus overhead lines, impose direct costs on utility operations. Second, the paramount concern with maintaining high PQR leads to conservative operations, for example, potentially economic exchanges of energy are foregone. It may be that sustaining high PQR across the board no longer makes economic sense. If we are now able to provide PQR locally more closely matched to the requirements of loads, the standards of the centralized grid can be rethought.

Our traditional electricity supply paradigm is one in which a standard level of PQR is delivered to all customers at all times in all places. One of the more radical ideas is that as sensitive loads can be supplied by more localized means, then the standards of the traditional centralized grid can be adjusted to better suit the objectives of the current grid, that is standards could be more in keeping with current objectives, notably high renewable penetration, competitive markets, etc. The desirable level of reliability may be lower than we enjoy today. Also, the level of PQR could be chosen based on objective criteria, such as the cost-benefit trade-off, rather than on traditional engineering standards alone.

NEW ENTITIES

Thoughts about a changing grid paradigm has led to proposals for a new entity in the grid, usually generically referred to as a *microgrid*. It would be one of three pillars for the smart grid, the other two being better operation of the traditional power system, or *macrogrid*, and more effective interaction between supply and demand, for example, through advance metering infrastructure. A possible definition for microgrids is:

> Microgrids are electricity distribution systems containing loads and DER, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded. *CIGRÉ C6.22 Working Group*

There are two key characteristics of a microgrid. It has both local generation and loads, which are under local control, and this system can function either grid connected or islanded.

Beyond microgrids, *per se*, there could in fact be multiple types of new entities emerging. Figure 2 shows a schematic of the traditional power system.

Figure 2: The Traditional Centralized Structure

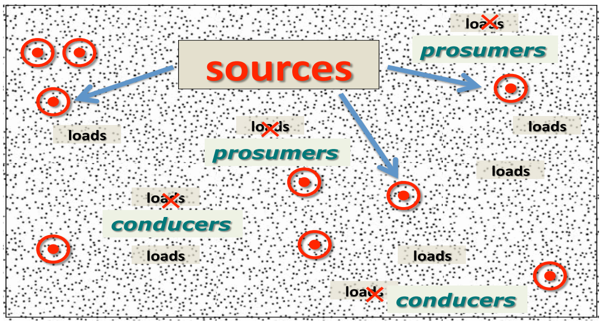
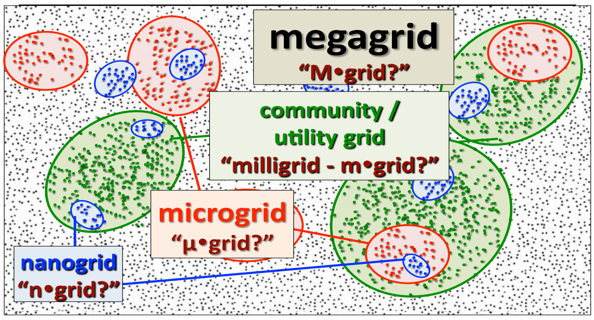


Figure 3: A Possible Dispersed Structure



The traditional structure has relatively few large generation assets (~1,400 in the case of the CAISO), shown by the target icons, and numerous small dispersed customer loads shown by the dotted background. CAISO additionally controls about 3,000 substations for a total of about 4,500 nodes. This structure began to change as small generating sources began to be installed at customer sites. Initial efforts to adapt tended to look at some of the background dots as relatively small sources at some time and small sinks at others, leading to usage like *prosumers* and *conducers*, i.e. nodes that are both producers and consumers at various times and under various circumstances. Under this view, the fundamental paradigm remains unchanged. Control of the system is still highly centralized, so the big innovation is that new small sources are added to the existing large sources, adding to its control problem.

Because managing a system with many such small sources, as well as the other issues listed above, thinking has moved to a structure wherein there are independent control nodes, called microgrids.

***μ·grid*:** These are shown in Figure 3 as red groupings of small sources and loads. They can appear anywhere in the traditional grid and are primarily characterized by their local control.

Definitions of microgrids have typically missed one important distinction between entities. In the graphic, the red entities are akin to traditional utility customers, that is they are downstream of a single meter, or at least a small number points of common coupling (PCCs). These might be termed “customer microgrids,” “true microgrids,” or as in the graphic as *μ·grids.*

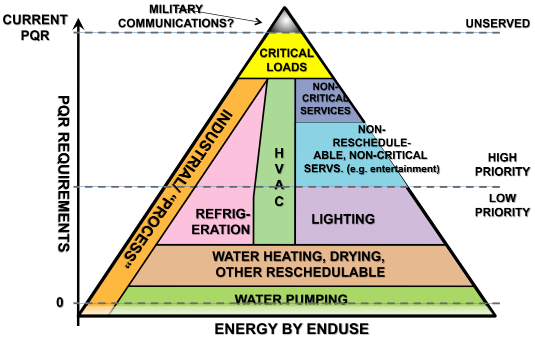
***m·grid*:** A second entity often also referred to as microgrids are also shown in green in Figure 3. These are controlled groupings of generation and loads and also able to island; however, an entity such as this that includes sections of the traditional distribution network is subject to different regulatory restrictions than μ·grids. Being subject to normal public utility regulation, such an entity must necessarily have commensurate operating procedures. Such an entity might be called a “utility microgrid” or a “community grid,” but since this is a fundamentally different institution, it is named a “milligrid” or *m·grid* in Figure 3.

***n·grid*:** Figure 3 shows a third blue type of grid in the hierarchy, the “nanogrid” or *n·grid.*[6] This electrical energy distribution network is something quite different, and yet is a common, familiar, and a growing distribution system that is often not ever considered a part of the power delivery system. Around us all, these networks exist as telecom systems that typically deliver 48 VDC to standard telephones, CAT5e Ethernet networks that deliver Power over Ethernet (POE+) at ~50-57 VDC to networked devices, USB-powered devices, vehicle networks, and others. These are low energy grids, typically DC, that are designed to deliver high PQR energy to certain devices that require it. In future buildings, nanogrids are likely to be ubiquitous and fully capable of delivery small amounts of energy with high PQR to compatible enduses. As nanogrids typically include communications and control, devices can change behavior to optimize the PQR of the whole nanogrid to optimally match supply and demand as conditions change.

***M·grid*:** Since n·grid, μ·grid, and m·grid all follow standard SI prefixes, it then becomes tempting to dub the traditional high voltage grid, the “megagrid” or *M·grid*, as shown in Figure 3.

HETEROGENEOUS PQR

Figure 4: A PQR Pyramid



The emerging structure of the power delivery system described above raises the possibility of tailoring PQR to the requirements of various loads, which is a radical departure from the current operating principles of power systems. Further, in the analysis of power systems, consideration of how the value electricity varies given the PQR requirements of the end-use served is much less common than consideration of the time and spatial variation in value. Nonetheless, it is intuitively appealing to think that delivering PQR tailored to the requirements of end uses, as is the case in the emerging paradigm, can generate higher economic benefits than universal PQR that never quite matches the requirements.

Consider the pyramid shown in Figure 4, which illustrates how various electricity uses might be classified according to their PQR requirements. Some common loads, such as pumping, are widely agreed to have low PQR requirements and appear at the bottom of the pyramid. Other loads can be much harder to classify; e.g., refrigeration is reschedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid, the exposed peak above current standards shows that not all requirements are currently met. The layout of enduses is highly speculative and simply intended to show how heterogeneous power quality (HeQ) might be considered. More important is the pyramid shape itself. It is clearly not a natural law that low PQR demanding loads vastly outnumber critical ones; however, if we behave in an economically rational manner, we would attempt to make them so. In other words, serving the low requirements loads at the bottom is cheap, and vice-versa for the sensitive loads at the top. There are three levels at which we might disaggregate PQR requirements: between customers who value it differently, between circuits in a building, and between various functions within a device. The variety of PQR preferences between customers is widely accepted and has led to interruptible tariffs. Multiple service qualities in a building is not common but it is seen in hospitals, which often serve critical loads on special circuits that have better back-up. The third level is more novel, but different functions within a device often have highly diverse requirements. For example, the thermostat and light in a refrigerator require high reliability while the compressor is a classic expendable load.

One of the factors that enables discrimination based on PQR needs in these grids is advances in communication technology. The needs of the grid can be expressed (e.g. through prices) to end use devices, and devices can change their behavior based on this and operational considerations for the optimal result. There is a need for standards development to enable more interoperability of small grids and the devices in them.

CONCLUSION

The familiar power delivery paradigm that has served industrialized economies magnificently for over a century is finally starting to appear in need of revision. Many factors are leading analysts to rethink its structure. One vision for the paradigm that might replace it leaves the high voltage meshed grid in place, but adds several new entities downstream of the substation. At present, these entities are loosely referred to as microgrids, or are barely considered a part of the electricity supply infrastructure. In general, they can be classified into at least three types of local grids: a *m·grid* which includes segments of the legacy distribution network, a *μ·grid* which is akin to a current customer site, and a *n·grid* which is any of many forms of alternative electricity distribution or separate power domains. The autonomously controlled assets of such local systems can provide power at multiple levels of PQR to various devices and so customize the power delivered to the requirements of the enduses. This in turn can free up the *M·grid* to operate at a level of PQR better suited to our current societal goals, decarbonization of electricity generation and efficient wholesale markets. Thus, tailoring PQR in this way offers two major potential advantages over our legacy homogeneous PQR delivery system, one by avoiding provision of unnecessarily expensive high PQR to loads that do not need it, and a second by freeing the traditional high voltage meshed grid from the treadmill of ever more demanding PQR. The end result can be less costly but more functional than the traditional approach.

BIBLIOGRAPHY

[1] Gellings, Clark, and Kurt E. Yeager. “Transforming the Electric Infrastructure,” *Physics Today*, Dec 2004.

[2] Details on California’s Renewable Portfolio Standard can be found at http://www.cpuc.ca.gov/PUC/energy/Renewables/overview.htm

[3] California Energy Commission. *Renewables Portfolio Standard Eligibility*, 3rd. ed., Sacramento CA, Jan 2008.

[4] Helman, Udi, et al. *Integration of Renewable Resources: Operational Requirements and Generation Fleet Capability at 20 % RPS*, California Independent System Operator, 31 Aug 2010.

[5] U.S. Department of Enegy. *The Potential Benefits of Distributed Generation and Rate-Related Issues That May Impede Its Expansion*, study pursuant to Section 1817 of the Energy Policy Act of 2005, Washington DC, Jun 2007.

[6] Nordman, Bruce. “Nanogrids, Power Distribution, and Building Networks,” seminar at Berkeley Lab, 24 Feb 2011, available at: http://eetd-seminars.lbl.gov/seminar/nanogrids-power-distribution-building-networks